

ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING



**Performance Assessment of Horizontal Subsurface Constructed wetland for
the treatment of Winery wastewater**

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in
Partial Fulfillment of the Requirements for the Degree of Master of Science in Water
Supply and Environmental Engineering.

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ABSTRACT

Wastewater from human dwellings and activities has been a primary target of many treatment technologies, including constructed wetlands. Constructed wetland technologies for wastewater treatment is characterized by specific conditions enabling simultaneous various physical and biochemical processes that are responsible for the removal and retention of pollutants. Thanks to its advantages such as simple construction, easy operation and cost effective maintenance, there is growing interest in the use of this technology for the treatment of wastewater from different sources including industries.

The specific characteristic of industrial wastewater (new pollutants, extreme concentration, low biodegradability, high toxicity) is a challenge for the application of constructed wetlands, and therefore research is necessary to assess their viability and optimize their design and operation. This study was undertaken to establish the efficacy of horizontal subsurface constructed wetlands in purifying winery wastewater, and to examine the effect of water depth and vegetation on the treatment efficiency.

The study used four pilot scale cells with water depth of 40 cm and 80 cm that were operated at the same hydraulic residence time of ten days. Two cells were planted with local macrophyte (*bossarus aethopium*) and the other two were left unplanted to be used as control. The constructed wetlands exhibited good removal efficiency with respect to all the major pollutants monitored i.e. COD, BOD, TSS, TDS, TKN, NH_4^+ , NO_3^- , TP and PO_4^{3-} . The data analysis indicated that the shallow wetland cells with a water depth of 40 cm had significantly higher performance for the removal of COD, BOD, TKN and NH_4^+ than the 80 cm deep cells. Also, the planted wetland cells showed better removal efficiency for the organic matter and nutrient than the unplanted cells.

The findings of this study showed positive results towards the use of HSSFCWs for the treatment of winery wastewater. The 40cm deep planted cell had better overall performance compared to the other cells and hence was used to design a large scale constructed wetland for Awash winery. STELLA modeling tool was used to simulate the hydrologic dynamics of the large scale constructed wetland.

DECLARATION

I declare that this thesis is my original work performed under the supervision of research advisor Dr. Agizew. The work has not been presented as a thesis for a degree in any other university in Ethiopia. Where material has been used from other sources, it has been properly acknowledged /referred.

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LISTS OF ABBREVIATIONS

ANOVA	Analysis of Variance
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CW	Constructed Wetland
EEPA	Ethiopian Environmental Protection Authority
EPA	Environmental Protection Authority
FWS	Free Water Surface
GWRDC	Grape and Wine Research and Development Corporation
H40p	40 cm deep planted cell
H40u	40 cm deep unplanted cell
H80p	80 cm deep planted cell
H80u	80 cm deep unplanted cell
HLR	Hydraulic loading rate
HRT	Hydraulic Retention Time
HSSFCW	Horizontal Subsurface Flow Constructed Wetland
L	Litter
Mg	Milligram
NH ₄ ⁺ -N	Ammonium Nitrogen
NO ₃ ⁻ -N	Nitrate Nitrogen
OLR	Organic Loading Rate
SD	Standard Deviation
SF	Surface Flow
SSF	Subsurface flow
TKN	Total Kjeldahl Nitrogen
TP	Total Phosphorus
TDS	Total Dissolved Solid
TSS	Total suspended Solids
US EPA	United States Environmental Protection Authority

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CHAPTER 1 INTRODUCTION

1.1 Background

Environmental pollution from untreated wastewater disposal is one of the most serious environmental issues. Various human activities, including domestic, agricultural and industrial result in the production of wastewater. Such activities, although needed for human development and welfare, lead to the release of objectionable materials that can cause environmental degradation and loss of quality of life.

Industries are one of the major sources that generate substantial proportion of wastewater. Industrial discharges are high in volume and contain a vast array of complex organic compounds and heavy metals. Hence, if they are released into the environment untreated can cause both human health and environmental disasters (UNESCAP, 1999). Industrial wastewaters have different characteristics depending on the type of industry. Thus, their treatment must be designed specifically for the particular type of effluent produced. This study is focused on wastewater effluent from wine industry.

Winery wastewater is a major waste stream resulting mainly from numerous cleaning operations that occur during the production stages of wine. The resulting effluent contains different types of principal contaminants. The environmental impact of winery wastewater is notable, mainly due to its high organic/ inorganic load, the large volumes produced and its seasonal variability. Consequently, their treatment requires particular attention and demands careful consideration of all available option (Margarida O. and Elizabeth D., 2011). With the increasing pressure from the environment regulations and the growing awareness of the negative impacts of concentrated seasonal discharge of waters containing high nutrient and organic loadings in the nearby water courses, this industry is facing greater restrictions related to the discharge of their wastewater.

Several treatments for winery wastewater are available, however the development of alternative technologies is essential to increase their efficiency and to decrease the investment and exploration costs (Coetzee *et al.*, 2004). Hence, criteria should be considered in the selection of the adequate technology, such as maximization of removal efficiency, flexibility in order to deal with variable concentration and loads, moderate capital cost, easy to operate and

maintain, small footprint, ability to meet discharge requirements for winery wastewater and also low sludge production (Andreottola *et al.*, 2009).

Constructed wetlands (CW) can be an attractive option, as they represent an efficient, low cost, low maintenance and energy systems for wastewater treatment. CWs also have the advantage of being able to accept seasonal flows without adversely affecting the functional aspects of the treatment system. CWs are characterized by specific conditions enabling simultaneous various physical and biochemical processes. This is the result of an engineered and controlled ecosystem that comprise a substrate (e.g. soil), supporting plant and microbial communities that work synergistically to treat wastewaters (Sim, 2003; US EPA, 2000; UN-HABITAT, 2008).

In recent years, thanks to its advantages, there is growing interest in the use of constructed wetlands for the treatment of various types of wastewater. Most of the early applications were for domestic and municipal wastewater, and that sector of the technology continues to grow at a rapid pace in many places. However, there are a growing number of applications dealing with animal and industrial waters, urban and agricultural waters, mine waters, groundwater remediation, and other applications. Site-specific designs that carefully consider factors such as hydrology, native plant species, water depth and seasonal temperature fluctuation can lead to enhanced removal of contaminants in the wastewater (Kadlec and Wallace, 2009). In this thesis, the viability of horizontal subsurface flow constructed wetland (HSSFCW) for the treatment of winery wastewater will be assessed.

1.2 Statement of the Problem

The specific characteristic of industrial wastewater (new pollutants, extreme concentration, low biodegradability, high toxicity) is a challenge for the application of constructed wetlands. Therefore, there is a need for research to test the viability of this system for different types of wastewater and optimize their design and operation. This study was undertaken to assess the efficiency of horizontal subsurface constructed wetlands (HSSFCW) for the treatment of winery wastewater. Wineries produce large volumes of wastewater characterized by high levels of organic matter, nutrients and solids. The discharge of effluent of such low quality untreated poses a serious threat to people's health and the quality of the environment. HSSFCW is expected to offer an effective and inexpensive alternative for winery wastewater treatment.

1.3 Objectives of the Study

1.3.1 General Objective

The general objective of this study is to examine the viability of HSSFCW for the treatment of winery wastewater.

1.3.2 Specific Objectives

The specific objectives of this study are:

- To characterize winery wastewater
- To evaluate the removal efficiency of selected plant species (*Borassus aethiopicum*) for selected water quality parameters
- To optimize the physical dimensions of HSSFCW for effective treatment
- To model the processes that determine the water balance dynamics of the system

CHAPTER 2 LITERATURE REVIEW

2.1 Nature of Winery Wastewater

During the production of wine from grapes, large quantities of liquid effluent are generated from various units of operation and processes. Winemaking is seasonally produced and typically involves crushing and pressing grapes, processing including maturation, clarification and bottling (GWRDC, 2011). The winery wastewater is generated mainly as the result of cleaning practices in winery, such as washing operations during crushing and pressing grapes, rinsing of fermentations tanks, barrels washing, bottling and purges from the cooling process (Margarida O. and Elizabeth D., 2011). The resulting effluent contains different types of principal pollutants which are product losses in the form of grape juice and wine itself, sub-product residues such as seeds, lees, tartar, etc. and products used in various processes such as filtration earth and cleaning and disinfection chemicals such as caustic soda and citric acid (GWRDC, 2011).

A high volume of wastewater is produced in winery industries. Studies have shown that wineries usually produce from 1 to 5 liters of wastewater per liter of wine (Di Stefano N, 2008). The figures vary from one winery to another, depending on the production period and the unique style of winemaking in different wineries. The characteristics of winery wastewater can also fluctuate significantly on a daily basis, depending on the activities in the winery (GWRDC, 2011). In general, wine distillery wastewaters are acidic, have a brown color, and their high organic content can cause considerable environmental pollution. The organic nature of the winery wastewater is commonly quantified by high chemical oxygen demand (COD) concentrations (500 to 45,000 mg/L) and elevated biological oxygen demand (0.4–0.9 of the COD value). In addition to COD and BOD pollution, wine distillery wastewaters contain variable amounts of total suspended solids (TSS) (12 to 7300 mg/L) (Shepherd et al., 2001). Large suspended matter of winery wastewater contains grape skins, leaves, stems, and seeds, while smaller suspended particles are mainly dead yeast cells and cell fragments (lees), grit, dirt and diatomaceous earth. Winery wastewaters have also been characterized for nutrients such as nitrogen, phosphorous and sulphur. High concentrations of these constituents make the possible discharge of wine distillery wastewaters into water bodies problematic, as they cause eutrophication and other adverse environmental effects (GWRDC, 2011).

2.2 Environmental Impacts of Winery Wastewater

Winery wastewater poses a serious environmental problem in wine-producing countries, if wineries dispose untreated wastewaters into streams or irrigation systems. This practice may cause pollution of surface and groundwater, soil degradation, damage to vegetation, and odor disturbances (Litaor et al., 2015). The trace elements and organic chemicals in Winery wastewater is generated from different individual processes in wine making, which produce different qualities of wastewater at different times. Table 2.1 outlines the main constituents and sources of winery wastewater and their possible impacts on the environment (GWRDC, 2011).

Table 2-1: Potential environmental impacts from winery wastewater

Winery waste characteristic	Indicators	Sources	Possible effects
Organic matter	BOD ¹ , COD ²	<ul style="list-style-type: none"> • Product loss – juice, wine, lees • Residues in cleaning waste • Residues in DE filter waste • Solids reaching wastewater drains including skins, seeds, etc 	<ul style="list-style-type: none"> • Depletes oxygen when discharged into water • May cause oxygen imbalance in soil leading to inefficient removal of organic contaminants from soil or impacts on plant health • Malodours if waste is stored in open lagoons or land applied
Alkalinity/ acidity	pH	<ul style="list-style-type: none"> • Product loss – juice and wine – acidic, pH 3.5 to 5.5 • Microbial metabolism of organic substrates during storage of wastewater further acidifies the wastewater 	<ul style="list-style-type: none"> • Death of aquatic organisms at extreme pH ranges • Affects microbial activity in biological treatment processes • Affects the solubility of heavy metals in the soil and availability
Nutrients	Nitrogen, phosphorous, potassium, sulphur	<ul style="list-style-type: none"> • Product loss – juice, wine, lees • Proteins removed from wine to prevent haze are a source of nitrogen and to a less extent phosphorous • Phosphate detergents and phosphoric acid 	<ul style="list-style-type: none"> • Eutrophication when discharged to water or stored in lagoons • N as nitrate and nitrite may be toxic to infants • Toxic to plants in large amounts • Can acidify soil over time • Potassium may affect soil structure, resulting in decreased infiltration
Salinity	EC ³ , TDS ⁴	<ul style="list-style-type: none"> • Alkali washing – caustic • Saline groundwater used for cleaning • Product loss – juice, wine, lees 	<ul style="list-style-type: none"> • Toxic to plants and animals • Affects water uptake by crops • Affects nutrient balance, i.e. soils and crops
Solids	TSS ⁵	<ul style="list-style-type: none"> • Product loss – juice, wine, lees • Residues in caustic/citric acid cleaning waste • Residues in DE filter waste • Solids reaching wastewater drains including skins, seeds, etc 	<ul style="list-style-type: none"> • Reduces soil porosity, leading to reduced oxygen uptake • Can reduce light transmission in water • Can smother habitat • Odour generated from anaerobic decomposition

Notes:

1. Biological oxygen demand
4. Total dissolved solids

2. Chemical oxygen demand
5. Total suspended solids

3. Electrical conductivity

The overall impact of contaminants in winery wastewater on environmental health and safety is apparent. In order to diminish the overall effect of these effluents and comply with wastewater legislations and guidelines, there is a need for adequate treatment before discharge. This can be achieved through the application of appropriate treatment processes, which will help to minimize the risks to public health and the environment (GWRDC, 2011).

2.3 Conventional Methods of Treating Winery Wastewater

Wastewater treatment plants (WWTP) plays an essential role in tackling the world wide problem of increasing water pollution. In WWTP, physical and biochemical procedures are applied in order to decrease or eliminate the organic matter levels, pathogenic organisms and improve water quality so that water can be reused or released into the environment with minimal consequences (Moura et al., 2009). Proper disposal of wastewater is necessary not only to protect the public's health and prevent contamination of groundwater and surface water resources, but also to preserve fish and wildlife populations, and for other beneficial users such as water-based recreation (Nemerow et al., 2009).

A wide variation in the type and extent of treatment are undertaken by the wine industries. This variation reflects local circumstances and requirements for discharge. The treatments may be used in different combinations (and sequences) but are generally grouped as primary, secondary and tertiary treatments. Winery wastewater is generally high in soluble bio-degradable organics, moderately high in suspended solids and variable in flow-rates. As such, it typically requires primary treatment such as surge management, screening and settling to deal with variable flows and remove suspended solids. In advanced primary treatment, chemicals may be added to add value to physical treatments. For example, clarification, following screening and sedimentation, can be aided by adding chemicals to promote the separation of colloidal material or the flocculation (agglomeration) of solids. Biological methods are used in secondary treatment to reduce the organic load and levels of nitrogen and phosphorus. Additional combinations of physical, chemical, and biological processes are used in tertiary treatment, if being recycled for a specific use to tailor the water for its next-use (GWRDC, 2011)

2.3.1 Physicochemical Methods

Various physicochemical processes are used to treat winery spent wash, each one operating in a different manner. The physicochemical treatment options that are used in the industry include coagulation-flocculation, electrodialysis, reverse osmosis (RO), nanofiltration (NF), photo-fenton and various ozonation processes (Litaor et al., 2015).

Coagulation and flocculation is a process designed to remove colloids from the wastewater. Coagulation is the first step in this process where the colloidal particles are destabilized so that the surface charges of the particles change. This causes the particles to attract one another to form larger particles called flocs. Flocculation is the second process where bridges are formed between the flocs to form larger agglomerates (Mohana *et al.*, 2009). Braz *et al.* (2010) conducted a study on winery wastewater using coagulation and flocculation as a processing step. It was found that this process successfully decreased the turbidity of the winery wastewater and total suspended solids. It did not, however, have any effect on the reduction of the COD.

Membrane filtration treatment processes are widely used in the water and wastewater industry. This process is used to separate colloidal and dissolved solids from water by means of a membrane using either pressure or an electrical current as the driving force. The process of separation is quite simple; the membrane operates as a filter, letting anything through it that is smaller than the pores of the membrane. Different types of membranes and also different techniques are available. Reverse osmosis (RO), nanofiltration (NF), microfiltration (MF) and electrodialysis are some of the membrane filtration processes used in the treatment of winery and distillery effluents (Shivajirao, 2012). Membrane-based separation techniques were investigated and yielded good results when applied to wine distillery wastewater and other agro industrial wastewaters (Nataraj *et al.*, 2006; Shivajirao, 2012; Ioannou *et al.*, 2013).

The photo-fenton is an advanced oxidation process that typically employs chemical oxidizing agents in the presence of an appropriate catalyst and ultraviolet light to oxidize or degrade the pollutant of interest. The irradiation of UV/Visible light strongly accelerated the rate of degradation of a variety of pollutants (Amilcar Machulek Jr., 2012). In ozonation process, organic pollutants are degraded through the infusion of ozone, a gas produced by subjecting oxygen molecules to high electrical voltage (EPA, 1980).

Physicochemical technologies have met with limited success because they are costly, require handling and disposal of the large amount of sludge left after treatment, and cause possible formation of harmful by-products. These processes also require highly trained personnel for running and maintenance, and are mostly suitable for very large wineries (Metcalf and Eddy, 2003; Litaor M.I, 2015).

2.3.2 Biological Methods

The objective of biological treatment of industrial wastewater is to remove or reduce the concentration of organic and inorganic compounds as well as pathogens from the wastewater (Metcalf and Eddy, 2003). Biological treatment systems for high strength wastewater depend upon a selection of microorganisms to digest complex organic matter. The success in this conversion is influenced by the environment the microbes are kept in (Ofoefule *et al.*, 2011).

Biological processes can either be aerobic or anaerobic; in some cases these two systems are used in combination (Mohana *et al.*, 2009). The basic principles for successful biological digestion are very similar for both the anaerobic process and the aerobic process. Both operations have a microbial consortium that requires a substrate (food) for growth and cell maintenance as well as an environment favorable to allow optimum function of the consortium. The main difference between the two processes is that aerobic digestion occurs in the presence of oxygen and anaerobic digestion does not (Els *et al.*, 2005). This difference in operation causes the species within the consortium to change; with an aerated environment the aerobic and facultative aerobic species become more prominent. Furthermore, as the consortium changes, with an aerated environment, the digestion process changes and as a result the products produced will differ (Parawira, 2004; Els *et al.*, 2005). The aerobic digestion process uses oxygen as an electron acceptor to produce energy during metabolism of the substrate. The majority (60%) of the energy available is used to produce new cells and between 40 – 50% of the carbon source present in the substrate is transferred into carbon dioxide (Parawira, 2004).

In the anaerobic digestion process an alternative electron acceptor is needed as there is no oxygen available. Often sulphur is used if it is available as well as carbon. The reduction of organic material, as carbon is used as the electron acceptor, results in the formation of methane (50 – 70%) and the oxidation of organic material will result in the production of carbon dioxide (25 – 45%). A very small percentage of the energy produced by the anaerobic digestion process is used for new cells (5 – 10%) (Parawira, 2004; Els *et al.*, 2005).

The aerobic biological systems include conventional activated sludge techniques, sequencing batch reactors (SBR), activated sludge in jet-loop bioreactors, rotating biological contractors (RBC), sequencing batch biofilm reactors (SBBR), fixed bedbiofilm reactors, membrane bioreactor (MBR) systems and air micro-bubble reactors. Methods based on anaerobic biological processes include anaerobic filters, up-flow anaerobic sludge blanket (UASB) reactors, anaerobic fixed bed reactors (AFBR), and anaerobic SBRs (Litaor M.I, 2015; Margarida O. and Elizabet D., 2011).

In activated sludge treatment oxygen is introduced to an aeration tank containing a microbe-rich sludge. Treated effluent is then clarified in a settling tank with some sludge reclaimed for reuse and the remainder disposed of (wasted). The Sequencing batch reactor (SBR) is an activated sludge process, in which equalization, aeration and sedimentation occur in the same tank in a time sequence. Treatment occurs in batches, rather than in the conventional continuous flow through a sequence of tanks (GWRDC, 2011). The MBRs are very compact systems and offer an alternative to conventional activated sludge processes. The electricity consumption and the operating life of the membranes are higher than those associated with traditional activated sludge systems, what may constitute a constraint to its application. The biological treatments such as SBR, MBR and UASB have been used to treat a variety of effluents including those from wineries (Margarida O. and Elizabet D., 2011).

Most biological treatment methods have some characteristics in common: they are relatively expensive, energy intensive, and they are not always able to deal with fluctuations in the hydraulic and pollution load (Litaor M.I, 2015; Di Stefano N, 2008, Margarida O. and Elizabet D., 2011).

2.4 Constructed Wetlands as an Alternative Wastewater Treatment Method

2.4.1 Definition and background

Constructed wetlands (CW) are non-conventional or natural technologies for wastewater treatment (Ronald W.C., 2006). They are engineered systems designed and constructed to utilize the natural functions of vegetation, soils and microbial populations to treat wastewater pollutants. CWs separate and transform contaminants by physical, chemical, and biological mechanisms that may occur simultaneously or sequentially as the wastewater flows through the system (US EPA, 2000). The processes involved in these technologies in order to eliminate wastewater pollutant tend to be similar to those used in conventional systems (aerobic or anaerobic biological degradation, oxidation and reduction reactions, sedimentation, filtration, etc.) which are combined with other naturally occurring processes of the ecosystems (photosynthesis, microorganism or plant assimilation, etc) (Vera et al., 2006).

Constructed wetland has emerged as a useful technology for wastewater treatment due to its advantages. It is a natural system that residuals feature processes that use minimal energy and minimal or no chemicals, and produce relatively lower amounts of residual solids (Ronald W.C., 2006). CWs can be created at lower costs than other treatment options with low-technology

methods where no complex technological tools are needed. The system is also environment friendly and relies on renewable energy source such as solar energy, and on wetland plants and micro-organisms, which are the active agents in the treatment processes (Torrens, 2015).

Constructed wetlands may be used for primary, secondary and tertiary treatment of wastewaters from different origins. Most of the early applications of CWs were for domestic and municipal wastewater, and that sector of the technology continues to grow at a rapid pace in many places. However, their application has been extended to other types of wastewater (Kadlec and Wallace, 2009). It has been demonstrated that CWs can improve the quality of different types of wastewater including agricultural (Eric R.R., 2016), tannery (Dotro et al., 2012), textile (Fibbi et al., 2012), Synthetic (Sultana et al., 2014), food processing (Skrzypiec K., 2017) at various levels of treatment.

2.4.2 Components of constructed wetland

A constructed wetland consists of a properly designed basin that contains water, a substrate, and, most commonly, vascular plants. These components can be manipulated in constructing a wetland. Other important components of wetlands, such as the communities of microbes develop naturally (US EPA, 2000).

Water: Water is the most important component in CWs because it links all of the functions in a wetland and the treatment efficiency of a CW depends on its characteristics. Small changes in hydrology have fairly significant effect on a wetland and its treatment effectiveness; because of the large surface area of the water and its shallow depth, a wetland system interacts strongly with the atmosphere through rainfall and evapotranspiration. The density of vegetation of a wetland strongly affects its hydrology by obstructing flow paths as the water finds its sinuous way through the network of stems, leaves, roots and rhizomes. When the substrates are flooded, the physical and chemical characteristics are altered. In a saturated substrate, water replaces the atmospheric gases in the pore spaces and microbial metabolism consumes the available oxygen. Since oxygen is consumed more rapidly, substrates become anoxic (without oxygen). This reducing environment is important in the removal of pollutants such as nitrogen and metals (US EPA, 2000).

Soil substrate/or porous media: The soil substrate or the porous media is an essential component of any CWs. Substrates used to construct wetlands include soil, sand, gravel, rock, and organic materials such as compost. Substrate performs the function of rooting material for plants, surface for microbial biofilm growth, screen organic and inorganic

suspended matter, distribute inflow and collect outflow water (US EPA, 2000; UN-HABITAT, 2008). Biological and chemical transformations of pollutants take place in substrates thereby removing wastewater constituents. The permeability of different substrates affects the movement of water in the wetland. The substrate must provide a suitable medium for successful plant growth and allow even infiltration and movement of wastewater. Poor hydraulic conductivity will result in surface flow and channeling of wastewater, severely reducing the effectiveness of the system (Sim, 2003). Media selection also depends on the requirement of adequate hydraulic conductivity to reduce the risk of clogging. Experience showed that soil and sand are very susceptible to clogging (US EPA, 2000).

Wetland vegetation/macrophytes: The presence of wetland plants has been hypothesized to play a key role in wastewater remediation. In addition to their aesthetic roles, wetland plants exhibit several properties which enhance wastewater treatment processes and thus make them an essential component of the treatment wetland. Wetland plants enhance the treatment process of wetlands in several ways such as filter wastes, regulate flow, provide surface area for microbiological treatment, provide shade and control algae growth, contribute oxygen to the cells, take up and store some of metals and nutrients from the wastewater (Sinclair, 2000). Plants in wetland systems have been viewed as storage compartments for nutrients where nutrient uptake is related to plant growth and production. Emergent plants utilize their roots to obtain sufficient nutrients from wastewater (US EPA, 2000).

Plant species selection has impacts on level of sedimentation, plant nutrient accumulation and on the creation of favorable environment for microorganism that facilitates microbial degradation of contaminants. Certain plant species appear to be more efficient in CW treatment systems and more tolerant of high pollutant concentrations than others. Plant species selected for constructed wetland systems should be hydrophyte plants that are suitable for local climatic conditions, tolerant of the concentration of nutrients and other constituents in the wastewater stream and have treatment potentials (US EPA, 2000). Some examples of macrophytes that are mostly used in constructed wetland systems are common reed (*Phragmites australis*), bulrushes (*Schoenoplectus* sp.), water hyacinths, cattails, Cyperus species and lilies (US EPA, 1993).

Microorganisms: The main role of pollutant removal in constructed wetland is attributed to microorganisms, which are attached either onto the roots of wetland plants or on the soil substrate where they catalyze chemical changes and conduct desirable modifications of

nutrients, metallic ions and other substances (Vymazal et al., 2006). In any wetland, the ecological food web requires microbes to function in all of its complex transformations of energy. The food web is fueled by influent wastewater, which provides energy stored in organic molecules. Microbes perform very important activities in wetlands, such as transforming a great number of organic and inorganic substances into innocuous or insoluble substances, alter the reduction-oxidation conditions of the substrate and thus affect the processing capacity of the wetland, and are involved in the recycling of nutrients. Some microbial transformations are aerobic (that is, they require free oxygen) while others are anaerobic (they take place in the absence of free oxygen). Many bacterial species are facultative anaerobes, that is, they are capable of functioning under both aerobic and anaerobic conditions in response to changing environmental conditions (US EPA, 2000).

Populations of microbes can expand quickly when presented with suitable environment and energy-containing materials. When environmental conditions are no longer suitable, many microorganisms become dormant and can remain dormant for years (Hilton, 1993).

2.4.3 Pollutant Removal Mechanisms in Constructed Wetland

The main pollutant removal mechanisms in CWs are physical, chemical and biological processes, including filtration, sedimentation, adsorption, volatilization and bioaccumulation by plants (plant uptake) or microorganisms (Stottmeister et al., 2003). CW has potential to remove different range of pollutants including organic matter, suspended solids, nitrogen, phosphorus, trace metals and nutrients. The different pollutant removal mechanisms in CW are depicted in table 2.2 (Cooper et al., 1996).

Table 2-2: Pollutant Removal Mechanisms in Constructed Wetlands

WASTEWATER CONSTITUENTS	REMOVAL MECHANISM
Suspended Solids	Sedimentation Filtration
Soluble organics	Aerobic microbial degradation Anaerobic microbial degradation
Phosphorous	Matrix sorption Plant uptake
Nitrogen	Ammonification followed by microbial nitrification Denitrification Plant uptake Matrix adsorption Ammonia volatilization (mostly in SF system)
Metals	Adsorption and cation exchange Complexation Precipitation Plant uptake Microbial Oxidation /reduction
Pathogens	Sedimentation Filtration Natural die – off Predation UV irradiation (SF system) Excretion of antibiotics from roots of macrophytes

Total suspended solids removal - The primary mechanisms of total suspended solids removal are flocculation, filtration and settling (US EPA 2000). In HSSF wetlands, incoming suspended matter is removed mainly through the mechanisms of filtration and sedimentation. Low water velocities, coupled with the presence of sand/gravel media in HSSF wetlands promote settling and interception of solid materials (Kadlec and Wallace, 2009).

Organic matter removal - the amount of organic material in the wastewater can be measured as chemical oxygen demand (COD), biochemical oxygen demand (BOD₅) and total organic carbon (TOC) (Kadlec and Wallace, 2009; GWRDC, 2011). Attached and suspended microbial growth is responsible for the removal of soluble organic compounds, which are degraded biologically both aerobically (in presence of dissolved oxygen) as well as anaerobically (in absence of dissolved oxygen). The oxygen required for aerobic degradation is supplied directly from the atmosphere by diffusion or oxygen leakage from the vegetation roots into the rhizosphere (Cooper et al. , 1996; Kadlec and Wallace, 2009).

Phosphorous removal - Phosphorus is present in wastewaters as orthophosphate, dehydrated orthophosphate (Polyphosphate) and organic Phosphorus. The conversion of most phosphorus to the orthophosphate forms is caused by biological oxidation (Metcalf & Eddy, 2003; Sim, 2003). The removal of phosphorus in constructed wetlands is achieved by adsorption,

complexation and precipitation reactions involving calcium (Ca), iron (Fe) and aluminium (Al) and by plant uptake. The capacity of wetland systems to absorb Phosphorus is positively correlated with the sediment concentration of extractable amorphous aluminium and iron (Fe). Although plant uptake may be substantial, the sorption of orthophosphate by anaerobic reducing sediments appears to be the most important process. The removal of Phosphorus is more dependent on biomass uptake in constructed wetland systems with subsequent harvesting (Sim, 2003).

With detention time of less than ten days, available data indicate that 30 to 50 percent phosphorus is removed in wetlands (WEF, 2001). The results of a research done by Miriam *et al.* (2002) on the phosphorus retention efficiency of CW treating agricultural drainage water, suggested that a minimum hydraulic retention time to retain at least 50% of the bio-reactive phosphorus was 7 days. The research also confirmed that if the HRT exceeded 10 days, the removal efficiency ranged from 50 to 90%, but decreased drastically and was often even negative, if the HRT was shorter than five days.

Nitrogen removal - Nitrogen (N) can exist in various forms, namely ammoniacal nitrogen (NH_3 and NH_4^+), organic nitrogen and oxidised nitrogen (NO_2^- and NO_3^-). Analytically, organic nitrogen and ammoniacal nitrogen can be determined together and are termed as total kjeldehal nitrogen (TKN). The distribution of the ammonia species is a function of the pH. At pH levels above 7, the ammonia gas (NH_3) is predominant, while at levels below 7, the ammonium ion (NH_4^+) is predominant (Metcalf & Eddy, 2003).

The most common removal of nitrogen is achieved through nitrification/denitrification, volatilisation of ammonia, storage in detritus and sediment and uptake by wetland plants. The central pathway for nitrogen removal occurs through nitrification/denitrification. At the root-soil interface, atmospheric oxygen diffuses into the rhizosphere through the leaves, stems, rhizomes and roots of the wetland plants thus creating an aerobic layer. Organic N is mineralized to NH_4^+ -N through ammonification in both oxidized and reduced layers. The oxidized layer and the submerged portions of plants are important sites for nitrification in which ammoniacal nitrogen is converted to nitrite N (NO_2^- -N) by the *nitrosomonas* bacteria and eventually to nitrate N (NO_3^- -N) by the *nitrobacter* bacteria, which is either taken up by the plants or diffuses into the reduced zone where it is converted to N_2 and N_2O by the denitrification process (Kadlec and Wallace, 2009; Chang-Gyun Lee, 2009; Sim, 2003)

Nitrogen removal efficiency of a constructed wetland is affected by several factors, such as temperature, detention time, dissolved oxygen and vegetation type (Langergraber, 2007; Chang-Gyun Lee, 2009). Temperature is one of the environmental factors that affect the rate of reaction and activity of microorganisms. The microbial activities related to nitrification and denitrification can decrease considerably at water temperatures below 15 or above 30 °C; and most microbial communities for nitrogen removal function at temperatures greater than 15 °C (Kuschik, 2003). According to Bitton (2005), the optimum temperature for nitrifiers growth is 25°C - 30°C. Hydraulic residence time also plays a critical role in nitrogen removal efficiency. Ammonium and TKN concentrations in treated effluent decrease dramatically with increase in wastewater residence time (Huang et al., 2000). Dissolved oxygen is another factor that influences nitrification process. Both steps in the nitrification process can proceed only if oxygen is present, and thus the actual nitrification rate may be controlled by the flux of dissolved oxygen into the system. Dissolved oxygen concentrations above 1.5 mg/l are essential for nitrification to occur (Kadlec and Wallace, 2009).

Sulfur removal- In addition to nitrogen and phosphorus, sulfur occurs in CW in different forms, but because of their impacts, sulfide and sulfate are the most important in wetlands (William and James, 1993). In wetland systems, sulfate reduction occurs due to the presence of sulfate reducing bacteria in the substrate coupled with sufficient organic material to stimulate their activity (Martha, 2003). These bacteria are a group of prokaryotic microorganisms that use electron donors to reduce sulfate. Sulfate reducing bacteria remove sulfate from the water column by metabolizing sulfate into living tissue or by reducing sulfur to produce energy (Simi and Mitchell, 1999).

Pathogen removal- Pathogens are removed mainly by sedimentation, filtration and absorption by biomass. Once these organisms are entrapped within the system, their numbers decrease rapidly, mainly by the processes of natural die-off and predation (Sim, 2003).

2.4.4 Types of constructed wetlands

Constructed wetland systems are generally classified as surface flow wetlands and subsurface flow wetlands (US EPA, 2000, Kadlec and Wallace, 2009). Surface flow systems are further subdivided based on the type of macrophytes that grow on them as floating macrophytes, submerged macrophytes and emergent macrophytes, whereas subsurface flow wetlands may be subdivided into horizontal flow wetlands and vertical flow wetlands based on the

hydrological mode of flow. A summary of the types of CWs is presented in Table 2.3 (Kadlec and Wallace, 2009).

Table 2-3: Main types of CWs for wastewater treatment

Type					
Water level	Free water surface			Subsurface	
Plants	Floating	Submerged	Emergent	Emergent	
Flow	Horizontal		Horizontal	Vertical	Hybrid Vertical + Horizontal Horizontal + Vertical

2.4.4.1 Surface Flow Wetlands

A surface flow (SF) or free water surface (FWS) wetland consists of a shallow basin, soil or other medium to support the roots of vegetation, and a water control structure that maintains a shallow depth of water. Water is visible at a relatively shallow depth above the surface of the substrate materials. Substrates are generally native soils and clay or impervious geotechnical materials that prevent seepage (Sim, 2003; US EPA, 2000).

SF wetlands look much like natural marshes and can provide wildlife habitat and aesthetic benefits as well as water treatment (US EPA, 2000). As the wastewater passes through the system, it is treated through the processes of sedimentation, filtration, oxidation, reduction, adsorption and precipitation. Because of the potential for human exposure to pathogens, FWS wetlands are rarely used for secondary treatment. The most common application for FWS wetlands is for advanced treatment of effluent from secondary or tertiary treatment processes (e.g., lagoons, trickling filters, activated sludge systems, etc) (Kadlec and Wallace, 2009).

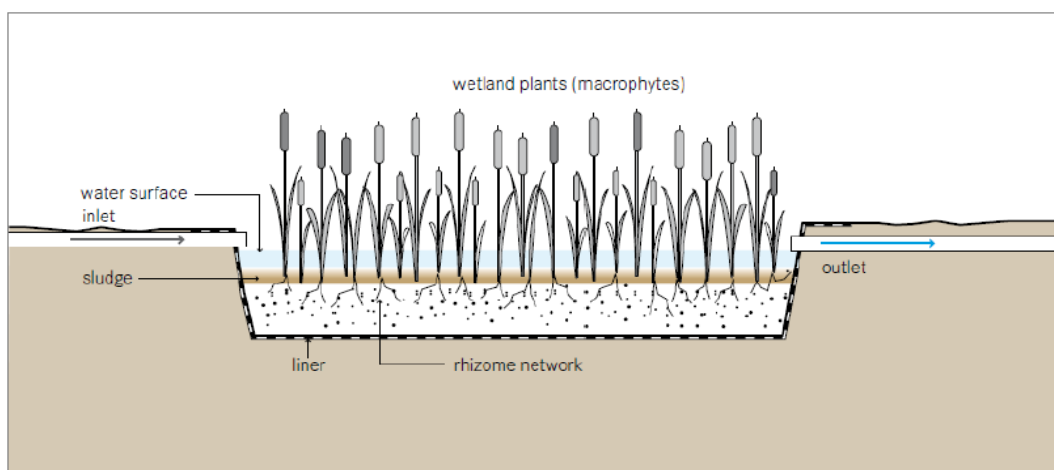


Figure 2-1: Schematic of FWS CWs (Tilley et al., 2014)

2.4.4.2 Subsurface Flow (SSF) wetland

In a subsurface flow (SSF) wetland, water flows from one end to the other end through permeable substrates which is made of mixture of soil and gravel or crusher rock. The substrate will support the growth of rooted emergent vegetation (Sim, 2003). The water level is designed to remain below the top of the substrate while it saturates the layer below. The saturated media and soil, together with the wetland plants roots, create conditions below the surface of the system that are conducive to treatment. SSF system is classified into two types based on the flow direction, as horizontal flow (HF) and vertical flow (VF) (US EPA, 2000). Based on the objective, this study is focused on horizontal subsurface flow constructed wetlands. Figure 2.2 shows schematic cross section of a HSSFCW.

The SSF type of CW is thought to have some advantages over the SF type. It has been claimed that the porous medium in SSF system provides greater surface area for treatment contact than is found in SF wetlands, so the treatment responses should be faster for SSF wetlands, which can, therefore, be smaller than a SF system designed for the same volume of wastewater. Because the water is not exposed during the treatment process, the risk associated with human or wildlife exposure to pathogenic organisms is minimized. Properly operated HSSF wetlands do not provide suitable habitat for mosquitoes. (US EPA, 2000; Kadlec and Wallace, 2009).

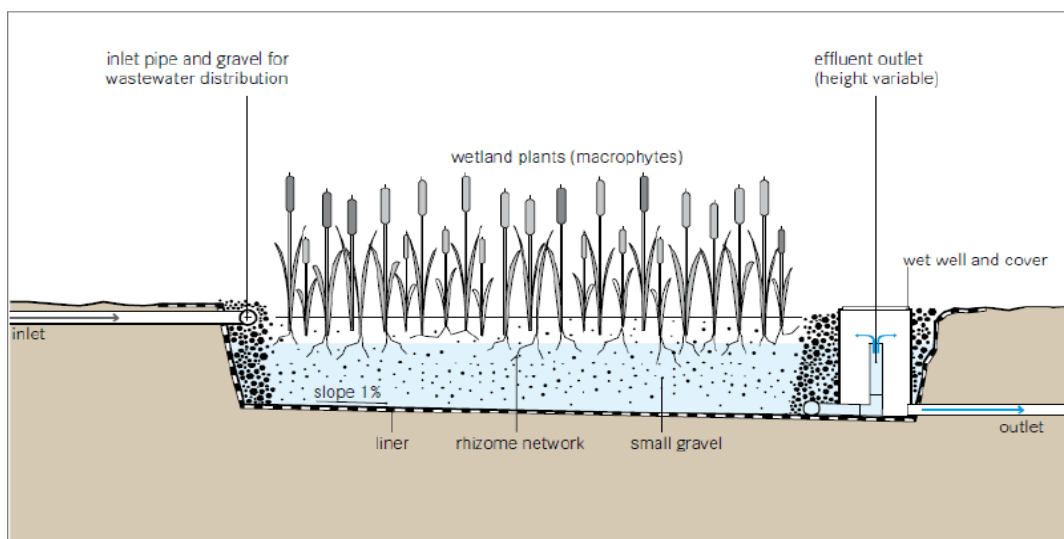


Figure 2-2: Schematic of HSSF CWs (Tilley et al., 2014)

As wastewater flows through the system, it will come into contact with a network of aerobic, anoxic and anaerobic zones. The aerobic zones will be around the roots and rhizomes of the wetland vegetation that leak oxygen into the substrate. During the passage of wastewater through the rhizosphere, the wastewater is cleaned by microbiological degradation and by

physical and chemical processes (Cooper et al., 1996). HSSF CW are effective in removing TSS, organic matter, microbial pollution and heavy metals. However, the removal of organic matter is limited by the shortage of oxygen (Vymazal, 2011).

2.4.5 Design and Operational Factors

The successful use of constructed wetland technology for the efficient treatment of wastewater depends mainly upon proper design and operational specifications (Kusler and Kentula, 1996). In terms of general design and operational parameters, SSFCWs are defined empirically based on previous experiences (Caselles, 2007). The most important design and operational parameters that can affect removal efficiency in SSFCWs are described below.

2.4.5.1 Primary Treatment

Primary treatment separates the suspended matter by physical operations mainly sedimentation. Raw wastewater contains suspended particulate heavier than water; these particles tend to settle by gravity under quiescent conditions. Primary treatment reduces suspended solids, organic load to the wetland and also equalizes raw wastewater quality and flow to a limited degree. The septic tank is the most common primary treatment used in small-scale constructed wetland worldwide (UN-HABITAT, 2008). The effectiveness of the sedimentation process is monitored through BOD₅, COD and TSS parameters. Performance of a sedimentation tank depends on influent characteristics and tank design. The factors to be considered in the design of the septic tank include the tank volume, hydraulic retention time and tank geometry. Sufficient tank volume is necessary so that after the maximum expected volume of sludge and scum has accumulated, the tank has a minimum of 24 hour fluid retention time for particulate settling. Rules of thumb for septic tank volume range from two to five times the daily average flow (US EPA, 2000; D'Amato et al., 2008). Tank geometry is also an important consideration that affects the residence time of solids in the tank. Septic tanks with a ratio of 3:1 length to width respectively will improve the removal of solids by reducing short-circuiting of raw wastewater and increasing the travel path of particles when they settle (Esther Omenka, 2010).

2.4.5.2 Hydrology

Hydrology is the most important variable in wetland design and in maintaining the wetland components to ensure they meet their performance requirements (Kadlec and Wallace, 2009). Hydrologic considerations include climate and weather, hydroperiod, hydraulic residence time, hydraulic loading rate, groundwater exchanges (infiltration and exfiltration), losses to the atmosphere (evapotranspiration), and overall water balance (US EPA, 2000).

Climate and weather

Because wetlands are shallow water bodies open to the atmosphere, they are strongly influenced by climate and weather. Rainfall, drought, freeze, and temperature can all affect wetland treatment. The high flows caused by heavy rains raise the water level and decreases the hydraulic residence time. On the other hand, ET losses increases pollutant concentration, temporarily lowers the water level and increases the residence time. High flows may also dilute some dissolved pollutants while increasing the amount of suspended material. Minimum temperatures limit the ability of wetlands to treat some, but not all, pollutants (US EPA, 2000).

Hydraulic Residence Time

The hydraulic residence time (HRT) of a treatment wetland is the average time that water remains in the wetland, expressed as mean volume divided by mean outflow rate (USEPA, 2000). In subsurface flow systems, the reactive volume is defined as the volume of water in the media in consideration of the void fraction that is defined as the fraction of the total media volume through which water can flow. The void fraction, also termed media porosity, ranges usually from 0.3 - 0.5 depending on the media material chosen (Vymazal, 1998). If short-circuiting develops, effective residence time may differ significantly from the calculated residence time (US EPA, 2000). Metcalf and Eddy (2003) suggested that the most effective HRT range is 4 to 15 days. Sim (2003) found that higher reduction efficiency for mass balances of N and P can be achieved if water retention time is more than 5 days. The HRT can be obtained by using equation 2.1 (USEPA, 1993).

$$\text{HRT} = \frac{n \times L \times W \times d}{Q_{av}} \dots\dots\dots (2.1)$$

Where:

n = porosity of media, as a decimal

L = Length of the bed, (m)

W = Width of the bed, (m)

d = Average depth of liquid in bed, (m)

Q_{av} = the average of the inflow and outflow, (m³/day)

HRT = Hydraulic retention time (d)

Hydraulic Loading Rate

The hydraulic loading rate (HLR) refers to the loading on a water volume per unit area over a specified time interval. Typically, hydraulic loading rates are specified in cm/d. The HLR

depends on the soil material (a critical parameter for subsurface flow wetlands), flow rate, area-size and hydraulic residence time. Lower HLRs or long HRTs result in better pollutant removal (ITRC, 2003). HLR is expressed as:

$$HLR = Q_i/A \dots\dots\dots (2.2)$$

Where, Q_i : wastewater inflow (m^3/d), and A is the wetland top surface area (m^2)

Water balance

The overall water balance for a constructed wetland is an account of the inflow, storage, and outflow of water. Water inflow to the wetland includes surface water (the wastewater), groundwater infiltration (in unlined wetlands), and precipitation. Storage is the surface water plus that in the pore spaces of the substrate. Outflow comprises evaporation from the water surface, transpiration by plants, effluent discharge, and exfiltration to groundwater. The wetland water balance is important for determining conformance with desired limits for HLR, hydroperiod range, HRT, and mass balances (USEPA, 2000). A simple water balance equation for a constructed wetland is expressed as:

$$S = Q + R + I - O - ET \dots\dots\dots (2.3)$$

Where:

- S = net change in storage
- Q = surface flow, including wastewater or storm water inflow
- R = contribution from rainfall
- I = net infiltration (infiltration - exfiltration)
- O = surface outflow
- ET = loss due to evapotranspiration

2.4.5.3 Design of Bed

CWs are usually designed to be of minimum size and cost in order to perform the required level of pollutant removal. Generally, the aspect ratio (length to width ratio) of a wetland bed is recommended to have a value between 0.25:1 and 4:1 (US EPA, 2000). SSF CW cells are usually designed with aspect ratios of 3:1 or less (Simi and Matchell, 1999). Miller and Black (1985) suggested that HSSFCWs should have a 3-4: 1 length to width ratio and be rectangular in shape, if minimal treatment area is available.

Theoretically, the bottom slope should match the slope of the water level to maintain a uniform water depth throughout the SSF. No research has been done to determine an optimum slope, but a slope of 1/2 to 1% is recommended for ease of construction and proper draining (US EPA, 2000).

2.4.5.4 Depth

In general, the depth of substrate in a subsurface flow constructed wetland is restricted to approximately the rooting depth of plants so that the plants are in contact with the flowing water and have an effect on treatment. However, Hydraulic Retention Time (HRT) is to be considered in the selection of the depth of the wetland. Virtually, HSSF wetlands have been designed with beds depths of 30-60 cm (Kadlec and Wallace, 2009). Most HF wetlands in Europe provide a bed depth of 60 cm (Cooper et al., 1996). Headley et al. (2005) predicted that plant depth can go as much as 76 cm in soil. However, the majority of plant roots remain in the top 20 cm of the bed.

2.4.5.5 Media selection

Media selection depends on the requirement of adequate hydraulic conductivity to reduce the risk of clogging (US EPA, 2000). Very small particles have very low hydraulic conductivity and create surface flow. Very large particles have high conductivity, but have little wetted surface area per unit volume of microbial habitat. Large and angular medium is inimical to root propagation. The compromise is for intermediate-sized materials generally characterized as gravels. It is recommended that the gravels are washed because this removes fines that could block the void spaces (UN-HABITAT, 2008). It is recommended that the media in the inlet and outlet zones should be between 40 and 80 mm in diameter to minimize clogging and should extend from the top to the bottom of the system. For the treatment zone, there does not appear to be a clear advantage in pollutant removal with different sized media in the 10 to 60 mm range (US EPA, 2000). Well graded media (containing all gravel sizes in the selected range) is better than poorly graded media as it offers greater pore space and provides good removal of particulate matter (Vymazal and Kröpfelová, 2008).

2.4.5.6 Inlet and Outlet structure

Inlet and outlet structures distribute the flow into the wetland, control the flow path through the wetland, and control the water depth. The inlet structure must be designed to minimize the potential for short-circuiting and clogging in the media, and maximize even flow distribution, whereas, the outlet structure must be designed to minimize the potential for short-circuiting, to maximize even flow collection, and to allow the operator to vary the operating water level and drain the bed (UN-HABITAT, 2008).

2.4.5.7 Vegetation

Vegetation and its litter are necessary for successful performance of constructed wetlands and contribute aesthetically to the appearance. Seeds, seedlings, entire plants, or parts of plants (rootstocks, rhizomes, tubers, or cuttings) can be used to establish wetland vegetation (US EPA, 2000).

The vegetation to be planted in constructed wetlands should fulfill the following criteria (UN-HABITAT, 2008):

- application of locally dominating macrophyte species;
- deep root penetration, strong rhizomes and massive fibrous root;
- considerable biomass or stem densities to achieve maximum translocation of water and assimilation of nutrients;
- maximum surface area for microbial populations;
- efficient oxygen transport into root zone to facilitate oxidation of reduced toxic metals and support a large rhizosphere.

2.5 System Dynamics Modeling of Constructed Wetlands

2.5.1 Background

A model is an idealization of a real situation, in which the most important components are identified and their interactions described and used as a tool to solve problems. The purpose of a model is not to replicate; it is impossible to put the complexity of the real world into computer. Instead the goal is usually to understand something about the behavior of the system and its response to change (Jorgensen, 2001).

System dynamics modeling (SD) can be defined as a way of thinking about a system as a web of interconnected pathways that affect fixed quantities of the system over time. A system is a collection of mutually interacting, consistent, and inter-reliant mechanisms that affect the whole structure of system. Dynamics can be termed as the degree that defines any change over time. SD is a way of conceptualizing the physical world in terms of the interconnection between its various elements (Antarpreet SJ., 2006).

2.5.2 STELLA software for CW Modeling

STELLA (Systems Thinking Educational Learning Laboratory with Animation) is a computer simulation program which provides a framework and an easy-to-understand graphical interface for observing the quantitative interaction of variables within a system. The graphical

interface can be used to describe and analyze very complex physical, chemical, biological, and social systems. Model builders and users, however, are not overburdened with complexity because all STELLA models are made up of only four building blocks: Stocks, flows, converters and connectors.

Stock— A stock is a generic symbol for anything that accumulates or drains over time.

Flow— A flow is the rate of change of a stock. It represents activities that determine the values of stocks.

Converter— Converters are system quantities that dictate the rates at which process operate and the stocks change. A converter is used to take input data and manipulate or convert that input into some output signal.

Connector —A connector is an arrow that allows information to pass between converters and converters, stocks and converters, stocks and flows, and converters and flows. They define the cause-effect relationships among the different components of the system (Antarpreet SJ., 2006).

2.6 The Process of Modeling

The process of building model is an iterative one in which the model is built in steps of increasing complexity until it stimulates the actual behavior of the natural system under consideration. The process of modeling starts with specifying the objective. The next step is to make a conceptual model of the problem, which defines the star variables in the system and the boundary of influence of the problem. The state variables are then represented by stocks. The process influencing the stocks is then connected to the stock using flows. Converters are then connected to the flows to define the feedback relationships. Various suitable numerical or empirical values or functions are assigned to the flows and converters, using knowledge based database or mental models. Each stock is then assigned an initial value. The model parameters are determined after defining the feedback relationships. If the model is found to need refinement, the empirical relationship can be changed, either by using existing data or the perceptions of the modeler. The next step in formulating the model is to initialize it, a process that involves ensuring that the model reproduces acceptable results as defined by a real time database. The last step includes verification (i.e., ensuring that there are no mechanical mistakes in the model) and validating the model, which helps to ensure its accuracy and usefulness (Ford, 1999).

CHAPTER 3 MATERIALS AND METHODS

3.1 Establishment of Pilot Constructed Wetland

3.1.1 Description of pilot-scale CW units

The experiment was conducted using four pilot-scale HSSF microcosm constructed wetlands. The wetlands were constructed by wooden material. Each wetland had a surface area of 1.2 m x 0.4 m with 3:1 length to width ratio (aspect ratio). This goes in line with the recommended aspect ratio of 0.25:1 to 4:1 (US EPA, 2000, Miller and Black, 1985). The values were selected to minimum size and cost. The design depth was 50 and 90 cm for shallow and deep beds. The corresponding wetted depths were 40 and 80 cm, respectively. The value of the shallow bed depth was derived from the root length of the selected plant, which was 34 ± 2 cm. The deep beds were designed to study the effect of depth.

Two units were planted with *Borassus aethiopicum* (palm tree) and the others two were kept unplanted to be used as a control. The bottom of the beds had an approximate of 1% slope from inlet to outlet to acquire hydraulic head-loss. Plastic liner was used as impermeable layer to block the flow of water out of the system other than the outlet. constructed wetlands must be sealed to avoid possible wastewater infiltration in the ground and also to prevent water from infiltrating into the wetland (US EPA, 2000).

All units were packed with 40-80 mm gravel media at the inlet and outlet of the wetlands and the main media was 20-30 mm gravel with a porosity of 50%. The gravel was filled up to a depth of 45 and 85 cm for the shallow and deep beds respectively. The media was washed before it was placed into the wetland beds to remove debris which can block the flow of wastewater through the media.

The influent was distributed via PPR plastic pipes of size 20 mm located at the top of each wetland cell. A weir pipe extending the full width of each cell disperses the wastewater over the surface of the cell to prevent short-circuiting. Table 3.1 summarizes the characteristics of each cell and indicates the names employed in the study to define each bed configuration. Figure 3.1 shows picture of the pilot scale HSSFCWs.

Table 3-1: Characteristics of wetland cell

Wetland Cell Name	Wetted Media Depth (cm)	B. aethiopicum	Main Media, gravel (mm)	Surface Area (m ²)
H40	40	Unplanted	20-30	0.48
H40P	40	Planted	20-30	0.48
H80	80	Unplanted	20-30	0.48
H80P	80	Planted	20-30	0.48



Figure 3-1: Pilot-scale HSSFCWs after plantation

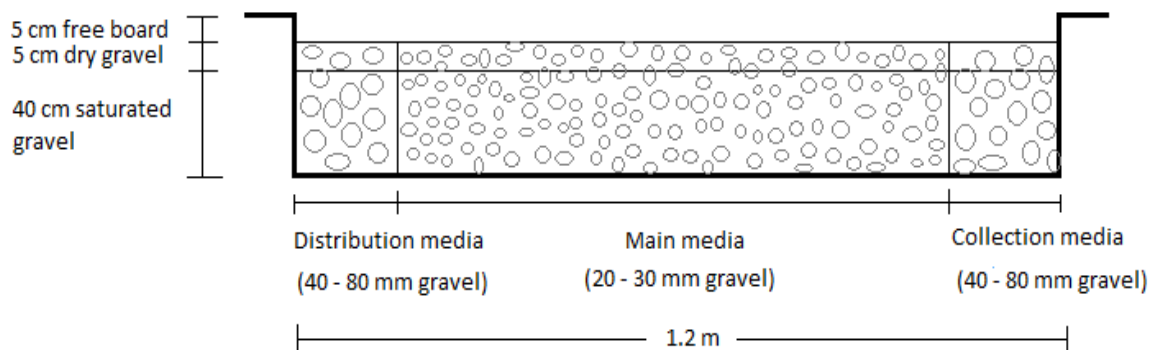


Figure 3-2: Schematic of 50 cm deep HSSFCW

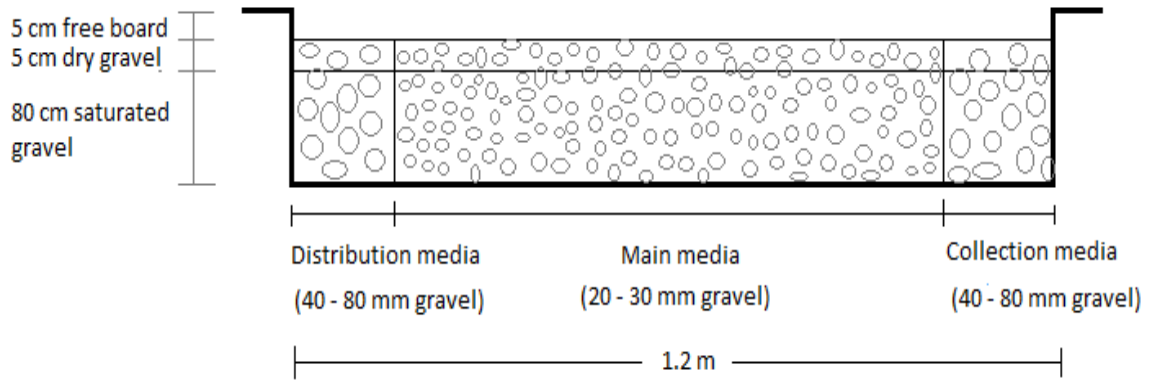


Figure 3-3: Schematic of 90 cm deep HSSFCW

In this study, *Borassus aethiopicum* (palm tree) was used as a wetland plant. For the plants to reach the stage in figure 3.1, it took about one year and six months (ten months in a seedling stock and eight months in the study site). The plant was selected based on its local availability and its potential to treat wastewater from literature. The plant's specimen samples were taken to Addis Ababa University (AAU) National Herbarium for species identification.

The plants were transplanted to the constructed wetlands. The wetland basins were first fed with tap water. Then, wastewater diluted with tap water at different proportions (10:90, 20:80, 30:70, 50:50, 75:25, 90:10, 100:0) was fed to the wetlands before fully wastewater was applied to the wetlands because gradual rather than sudden increase in the concentration of wastewater applied reduces shock to the vegetations and provide adaptation period. The readiness of the plant for the actual experimental procedure was illustrated by the healthy leaves and stem and by the growth of new leaves and inflorescence.

3.1.2 Experimental start-up

The four pilot scale units were built to receive winery wastewater obtained from Awash Winery from a septic tank with a capacity of 800 L, which serves as a primary treatment for settlement of suspended solids. The wastewater is subsequently released via PPR plastic pipe of size 20 mm to an equalization tank to be distributed to each cell for treatment. The equalization tank controls the flow rate to the wetland cells. The flow rate entering the constructed wetlands was controlled using gate valves.

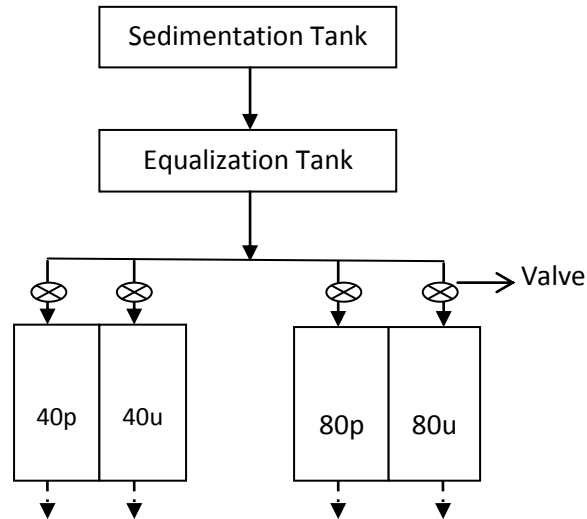


Figure 3-4: Layout plan of the experimental setup

The wastewater was loaded onto the 40 cm and 80 cm deep wetlands with the same detention time (HRT) of ten days. After HRT is selected, the average flow rate (Q_{av}) of the wetland can be calculated using equation 2.1. The average flow rate of the wetlands for the 40cm and 80cm deep wetlands were 9.6 L/d and 19.2 L/d, respectively. The wastewater feeding was continuous during the entire period of the study.

The daily flow rate was adjusted and checked manually using a measuring cylinder and a stopwatch. The wetland cells were packed with main media of 20-30 mm gravel with a porosity of 50%. Porosity is equal to void volume/total volume and is expressed as percentage. The void volume of the wetlands was estimated by draining the wetland cells and measuring the water volume of each cell. Figure 3.5 shows pictures of the experimental setup.



(a)



(b)

Figure 3-5: Influent Sedimentation tank and Equalization tank

3.2 Water Sampling and Analysis

3.2.1 Sample Collection and Analysis

Samples were collected from the influent wastewater situated at the equalization tank and from the treated effluents coming out of each wetland unit. The samples were collected using one liter plastic sampling bottles and transported to the laboratory for analysis. The grab samples were taken for water quality analysis with a frequency equal to the HRT after feeding the wastewater.

Analysis of the collected samples was carried out for selected physicochemical water quality parameters. Three replica samples were taken for the analysis of each parameter. The parameters that were examined are: pH, temperature, biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), total kjeldahl nitrogen (TKN-N), ammonium (NH₄⁺-N), nitrate (NO₃⁻-N), phosphate (PO₄³⁻-P), total phosphorus (TP), Total Suspended Solids (TSS) and Total dissolved Solids (TDS). The parameters were analyzed in JIJE LABOGLASS Pvt. limited company. The parameters analyzed and the test methods are described below.

Test Methods:

COD	APHA 5220 B. Open Reflux Method
BOD	APHA 5210 B. 5-Day BOD Test
TKN	APHA 4500-Norg C. Micro-Kjeldhal Method
NH ₄ ⁺ -N	MgO Distillation
NO ₃ ⁻ -N	APHA 4500-NO ₃ -B Ultraviolet Spectrophotometric Screening
TP	APHA 4500-P.E persulfate digestion Ascorbic Acid Colorimetric
PO ₄ ³⁻	APHA 4500-P.E Ascorbic Acid Colorimetric

TSS APHA 2540 D. Total Suspended Solids Dried at 103-105°C
 TDS APHA 2540 C. Total Dissolved Solids Dried at 103-180 °C
 PH APHA 4500 H+B Electrometric

The removal efficiency of the wetlands for each wastewater quality parameters was calculated using the following formula:

$$\text{Efficiency (\%)} = \frac{C_i - C_e}{C_i} * 100 \dots\dots\dots (3.1)$$

Where: C_i = is the concentration of the waste material in the influent (after pretreatment)
 C_e = is the concentration of the waste material in the effluent

For analysis of physicochemical parameters, sample collecting bottles were cleaned thoroughly by repeated washing with tap water and distilled water. Effluent collecting jerry cans were also washed regularly and thoroughly to avoid algae and slime formation. The parameters were taken for analysis on the day of sampling to ensure the results generated are accurate.

3.2.2 Statistical Analysis

Statistical analysis was performed using SPSS® statistics version 24 software package. One-way analysis of variance (ANOVA) at 95% confidence level was used to compare the performance of the constructed wetlands concerning the removal of the selected water quality parameters.

3.3 Modeling Hydrologic Dynamics of the System

3.3.1 Model development

In this study, STELLA® version 9 software was used to model the hydrological conditions in the constructed wetland. The first step in the modeling processes was to develop a conceptual model to capture the processes involved in the system. After setting up the model in a flow diagram form, STELLA program converts the graphical representation to the basic equations.

The system under consideration here is affected by inflow, outflow, precipitation and evapotraspiration processes. A conceptual water balance model is shown in figure 3.6 below.

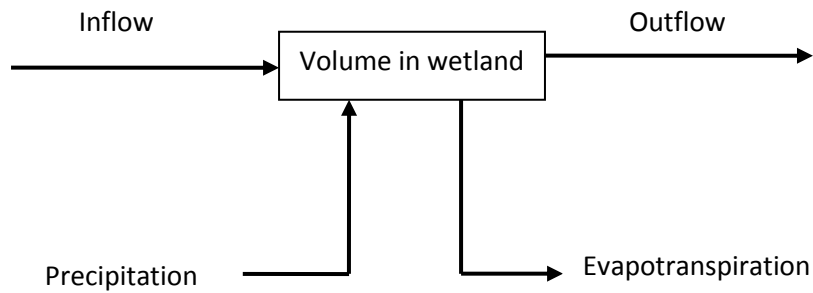


Figure 3-6: Conceptual model of water balance

3.3.2 Mathematical equations

The mathematical equations for the water balance in the wetland can be expressed as follows:

$$Q_i - Q_o + P - ET = [dV/dt]$$

where,

Q_i = influent wastewater flow, volume/time,

Q_o = effluent wastewater flow, volume/time,

P = precipitation, volume/time

ET = evapotranspiration, volume/time

V = volume of water, and

t = time

Ground-water inflow and infiltration are excluded from the equation because of the impermeable barrier.

3.3.3 Verification of simulation model

Verification is the task of determining if the implementation of a model has been done correctly. In model verification, the answer to the question “does this make sense given what I know about the conceptual model and the real world system?” is the one which is most important. Verification data need to be generated to see if the model outputs make sense (Thacker B.H., 2004). In this study the inputs that were varied were inflow rate and wetland surface area. The parameters were varied while keeping other parameters constant.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Influent Wastewater Characteristics

To evaluate the treatment performance of the constructed wetlands, selected physicochemical parameters of the wastewater from the influent and effluents were analyzed in the laboratory. The average concentrations of parameters monitored before pre treatment and also at the input and at the output of the pilot wetlands are summarized in table 4.1.

Table 4-1: Mean concentrations of influent and effluent of the 40 and 80 cm deep beds

Parameter	Influent (mg/L)	Effluent concentration (mg/L)			
		H40p	H40u	H80p	H80u
COD	2573±364	448±32	612±43	674±48	823±61
BOD	1056±201	275±22	381±24	406±28	510±31
TKN	68±14	25±3.3	37±4	35.6±3.7	47±4.6
NH₄⁺	43±12	12±1.6	23±3.3	21±3.5	29.4±4.2
NO₃⁻	22±5	13.8±2.3	17±2.8	11.4±2	15.6±2.4
TP	12±4	3±0.5	5.2±0.8	2.71±0.4	5±0.9
PO₄³⁻	5±2	0.8±0.2	2.1±0.5	0.7±0.06	2.04±0.4
TSS	71±8	24±4	31.1±6	22.4±3	27.8±4
TDS	842±274	343±47	401±32	330±35	382±22
pH	5.6±0.5	6.1±0.2	6.6±0.3	6.5±0.3	6.9±0.4

The result showed that the concentrations of the parameters were variable, with COD load of 2573±364 mg/L and BOD₅ load of 1056±201 mg/L. The variations come up because winery operations vary by season, by days of the week and also by the time of day depending on the activities in the winery. As a result, the different parameters of the wastewaters also vary (GWRDC, 2011). The average organic loading rate of COD and BOD of the influent is 51.46 g/m².d and 21.12 g/m².d, respectively for the 40 cm deep cells, and 102.9 g/m².d and 42.24 g/m².d, respectively for the 80 cm deep cells.

Winery wastewater is also characterized by nitrogen and phosphorous contents. The findings of this study showed that the mean influent concentration of TKN, $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, TP and PO_4^{3-} was 68 ± 14 mg/L, 43 ± 12 mg/L, 22 ± 5 mg/L, 12 ± 4 mg/L and 5 ± 2 mg/L, respectively. The mean organic loading rates of these parameters are 1.36 $\text{g/m}^2\cdot\text{d}$, 0.86 $\text{g/m}^2\cdot\text{d}$, 0.44 $\text{g/m}^2\cdot\text{d}$, 0.24 $\text{g/m}^2\cdot\text{d}$, and 0.1 $\text{g/m}^2\cdot\text{d}$, respectively for the 40 cm deep cells, and 2.72 $\text{g/m}^2\cdot\text{d}$, 1.7 $\text{g/m}^2\cdot\text{d}$, 0.88 $\text{g/m}^2\cdot\text{d}$, 0.48 $\text{g/m}^2\cdot\text{d}$, and 0.2 $\text{g/m}^2\cdot\text{d}$, respectively for the 80 cm deep cells.

The influent concentration for TSS and TDS was 71 ± 8 mg/L and 842 ± 274 mg/L, respectively with mean organic loading rate of 1.42 $\text{g/m}^2\cdot\text{d}$ and 16.84 $\text{g/m}^2\cdot\text{d}$, respectively for the 40 cm deep cells, and 2.84 $\text{g/m}^2\cdot\text{d}$ and 33.7 $\text{g/m}^2\cdot\text{d}$, respectively for the 80 cm deep cells. The average pH value of the influent wastewater was 5.6.

4.2 Treatment Efficiency of pilot-Scale HSSF Constructed Wetlands

4.2.1 Biological Oxygen Demand and Chemical Oxygen Demand

As shown in table 4.1, the mean BOD_5 values of the effluent from H40p, H40u, H80p and H80u are 275 mg/L, 381 mg/L, 406 mg/L and 510 mg/L, respectively and the mean effluent values for COD are 448 mg/L, 612 mg/L, 674 mg/L and 823 mg/L, respectively. The results indicated that the mean percentage removal of BOD_5 from H40p, H40u, H80p and H80u was 74%, 64 %, 61.5 % and 52 %, respectively. Similarly, the mean percentage removal of COD was 82.5 %, 76 %, 74 % and 68 %, respectively (figure 4.1).

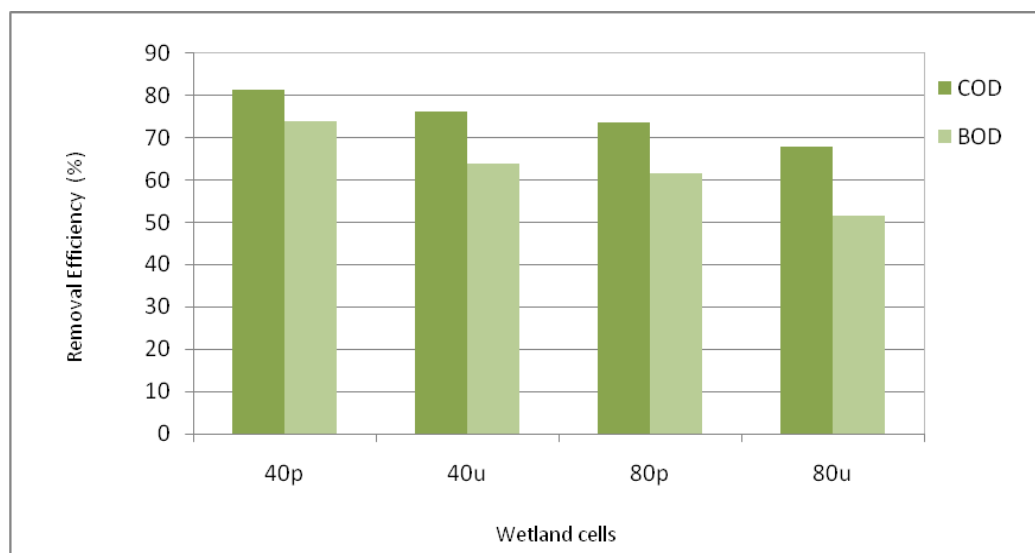


Figure 4-1: BOD_5 and COD removal efficiency

The result indicated that the systems had considerable removal efficiency for organic matter. In both cases the planted cells showed better removal of BOD₅ and COD than the unplanted cells when compared within the same depth. Statistical analysis showed that there was a significant difference ($p < 0.05$) in BOD₅ and COD removal between the cells with the presence of plant. Since BOD removal is enhanced under aerobic conditions, the superior treatment afforded by the planted cells could be due to plant translocation of oxygen, there by stimulating the breakdown of carbonaceous compounds. Plants provide a number of useful functions in treatment wetlands, such as the release of oxygen from roots and an increase in the sites available for bacteria (Kadlec and Wallace, 2009). Brisson *et al.* (2009) reviewed 16 experimental studies that assessed BOD and COD treatment performance of planted versus non planted subsurface flow constructed wetland systems. The studies showed a significant and positive effect of macrophytes on pollutant removal.

The result of the study showed that water depth is also likely to influence the efficiency of wetland in BOD₅ and COD removal. This can be because depth affects oxygen diffusion at air water interface, which might be the reason for the better performance of the H40 cells when compared to the H80 cells. Statistical analysis showed that there was a significant difference ($p < 0.05$) in BOD₅ and COD removal between the cells with depth difference.

The finding was similar to that of two side-by-side studies conducted in Tennessee and in Barcelona. The study in Tennessee utilized 14 HSSF wetlands, 7 operated at 30 cm and 7 at 46 cm. the wetlands were operating in parallel at different loading rates (Kadlec and Wallace, 2009). The study conducted in Barcelona was treating municipal wastewater and consists of wetlands with a depth of 50 cm and others with a water depth limited to the rooting depth of the plants, which was 27 cm. All were operating at the same hydraulic loading (García *et al.*, 2004). In both studies the results showed greater removal of organic matter in the shallow cells.

In this study, the effluent concentration values of BOD₅ and COD from the wetlands were compared with discharge limit values set by national environmental quality standard for winery wastewater effluent. The discharge limit values were 60 mg/L for BOD₅ and 250 mg/L for COD. But, the effluent values from the constructed wetlands do not meet this standard. The reason might be due to the organic loading rate used in this study is greater than the recommended values. The organic loading rate recommended by US EPA (1998) for BOD₅ and COD is 11 g/m².d and 20 g/m².d, respectively. The values used in this study are 21.12g BOD/m².d and 51.46 g COD/m².d for the 40 cm deep wetlands, and 42.24g BOD/m².d and 102.92 g COD/m².d for the 80 cm deep wetlands.

4.2.2 Total Suspended Solid and Total Dissolved Solid

The mean influent and effluent values of the constructed wetlands for TSS and TDS is presented in table 4.1. From the results the mean removal efficiency of the wetlands for these parameters is shown in figure 4.2.

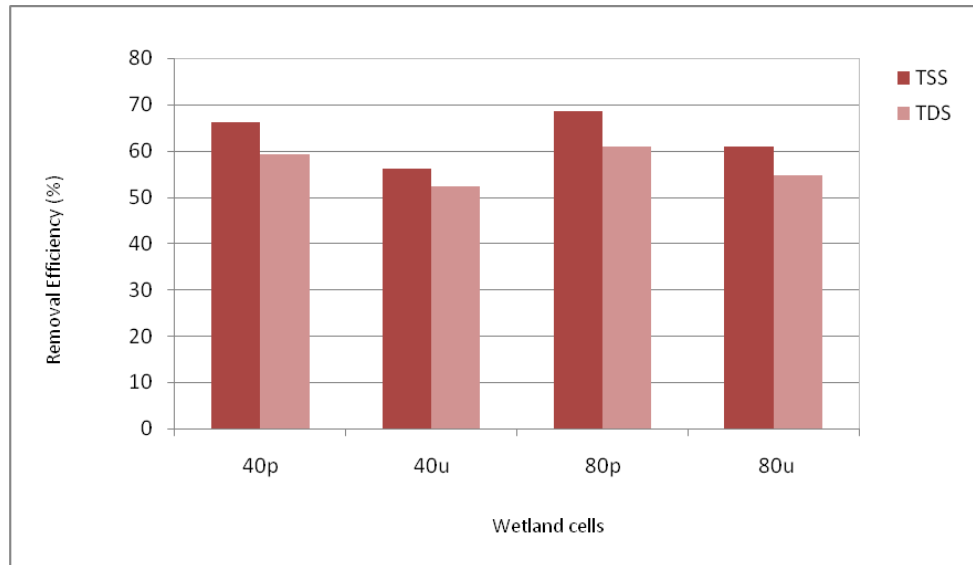


Figure 4-2: TSS and TDS removal efficiency

As shown in figure 4.2, the percentage removal of the H40p, H40u, H80p and H80u cells for TSS was 66 %, 56 %, 68.5 % and 61%, respectively and for TDS was 59 %, 52 %, 61 % and 54.6 %, respectively. From the results, it can be observed that the systems had significant removal efficiency for TSS and TDS. Statistical analysis showed that there was no significant difference ($p>0.05$) in percentage removal of both TSS and TDS between the planted and unplanted wetlands, and also between the 40 cm and 80 cm deep wetlands. This can be because the removal of these particulates is mainly due to physical processes such as sedimentation and filtration.

Concentrations of TSS and TDS from the effluents of the experimental study were compared with the national effluent emission standard for winery wastewater set by EEPA. The discharge limit values were 60 mg/L for TSS and 250 mg/L for TDS. The standards were effectively met by the effluents from all four constructed wetlands.

4.2.3 Total Kjeldahl Nitrogen, Ammonium Nitrogen and Nitrate Nitrogen

To analyze the nitrogen removal efficiency of the HSSF wetlands, values of total kjeldahl nitrogen (TKN), ammonium nitrogen ($\text{NH}_4^+\text{-N}$) and nitrate nitrogen ($\text{NO}_3^-\text{-N}$) from the influent and effluent points were evaluated. Table 4.1 shows the mean influent and effluent

concentrations of each wetland cell. The percentage removal of nitrogen in the wetlands is shown in figure 4.3.

Referring to the figure, percentage concentration removal of TKN was 63 %, 45.6 %, 47.6 % and 31 % for H40p, H40u, H80p and H80u cells, respectively. From the results, it was observed that the H40 cells had higher concentration removal than the H80 cells, and the planted cells showed better concentration removal than the unplanted. Statistical analysis showed that the effect of depth and plant was significant ($p < 0.05$) in the percentage removal of TKN. The greater TKN removal of the H40 when compared to the H80 can be due to the better diffusion of oxygen in shallow depth, which is favorable for nitrogen removal via nitrification. Wetland plants also influences nitrogen removal because of uptake associated with growth.

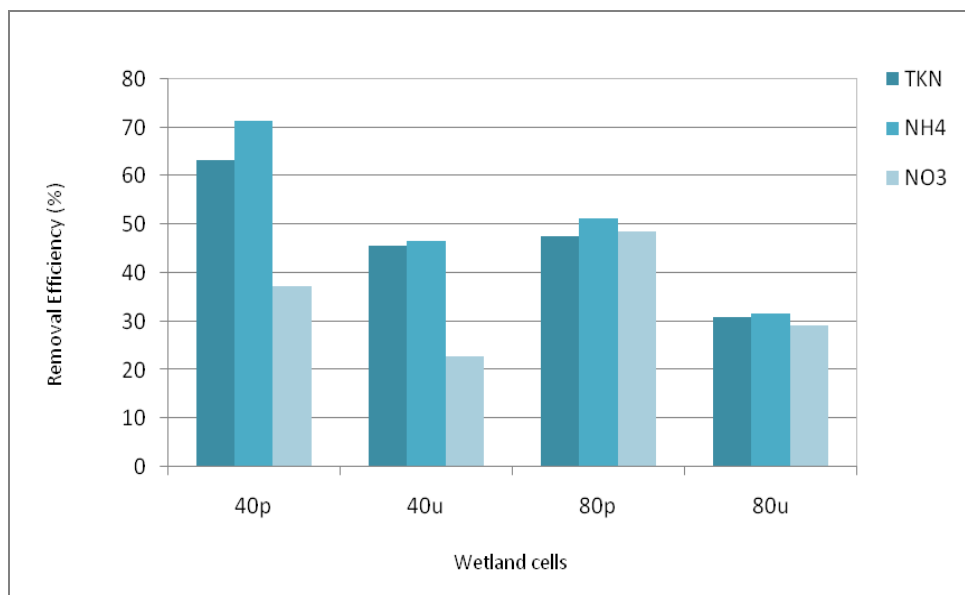


Figure 4-3: TKN, NH_4^+ and NO_3^- removal efficiency

In the same way, percentage removal of NH_4^+ -N was 72 %, 47 %, 51 % and 32 % for H40p, H40u, H80p and H80u cells, respectively. As shown in figure 4.3, the 40 cm deep cells had better concentration removal than the 80 cm deep cells and the planted beds showed positive removal when compared to the unplanted. The result indicated that there was a statistical significance of depth and plant ($p < 0.05$) in the percent removal of NH_4^+ -N. In constructed wetlands, NH_4^+ -N is mainly removed by nitrification-denitrification processes. Nitrification implies the oxidation of ammonia to nitrate under strict aerobic conditions and is performed in two sequential oxidative stages: ammonia to nitrite and nitrite to nitrate. The routes by which oxygen can gain entry to the water column for nitrification of ammonia are atmospheric diffusion and plant oxygen (Kadlec and Wallace, 2009; Chang-Gyun Lee, 2009). In this study, the

greater ammonia concentration removal of the H40 cells compared to H80 is likely because CWs with a lower depth having higher levels of dissolved oxygen. This can be due to the diffusion path between the surface and CW bed being shorter along with the oxygen release by macrophytes. Removal of nitrogen by volatilization could not have been possible as volatilization of nitrogen in the form of ammonia is insignificant below pH value of 7.5 (Cooper et al., 1996).

A similar study has been conducted by Garcia et al. (2004) on HSSF constructed wetlands treating urban wastewater. The wetlands had a depth of 27cm and 50cm. In the study, the percentage removal of ammonia obtained was 40-50% in the 27 cm deep wetlands and 25-30% in the 50cm deep wetlands. The result showed greater removal of ammonia in the shallow cells compared to the deep ones despite the shorter detention time.

From figure 4.3, the percentage removal of NO_3^- -N was 37 %, 23 %, 48.6 % and 29 % for H40p, H40u, H80p and H80u cells, respectively. The result indicated that the deeper wetlands had a slightly higher concentration removal than the shallow wetlands, and the planted cells showed better concentration removal when compared within the same depth. However, all were not significantly different ($p > 0.05$). In SSF systems, nitrate is reduced to gaseous nitrogen by facultative anaerobes via biological denitrification process. The microorganisms involved in denitrification switch to oxygen as terminal electron acceptor when the environment changed to aerobic condition, hence denitrification is best conducted in anaerobic condition (Kadlec and Wallace, 2009; Bitton, 2005; Chang-Gyun Lee, 2009).

In this study, the effluent concentration values of total kjeldahl nitrogen, ammonium nitrogen and nitrate nitrogen were compared with discharge limit values set by national environmental quality standard for winery wastewater effluent. The discharge limit values were 40 mg/L for total kjeldahl nitrogen and 20 mg/L for ammonium and nitrate. The findings of this study showed that for total kjeldahl nitrogen and nitrate nitrogen, the standard values were met by all wetland cells, except by H80u for total kjeldahl nitrogen. For ammonium nitrogen, except from H40p, the obtained effluents from the other wetlands did not meet the standard values set by EEPA. The lower removal of ammonium might be due to the HSSF wetlands limited capacity to oxidize ammonium because of limited oxygen transfer. Oxygen may be depleted by heterotrophic activity, as well as nitrification.

4.2.4 Total phosphorous and Phosphate

The mean total phosphorus (TP) and orthophosphate ($\text{PO}_4^{3-}\text{-P}$) concentrations values from the influent and effluent of each wetland cells was presented in Table 4.1. The mean influent concentration was 12 mg/L for TP and 5 mg/L for $\text{PO}_4^{3-}\text{-P}$. The mean concentration values of the effluent from H40p, H40u, H80p and H80u are 3 mg/L, 5.2 mg/L, 2.7 mg/L and 5 mg/L, respectively for TP and 0.8 mg/L, 2.1 mg/L, 0.7 mg/L and 2.04 mg/L, respectively for $\text{PO}_4^{3-}\text{-P}$. The mean percentage removal efficiency of the wetlands is shown in figure 4.4.

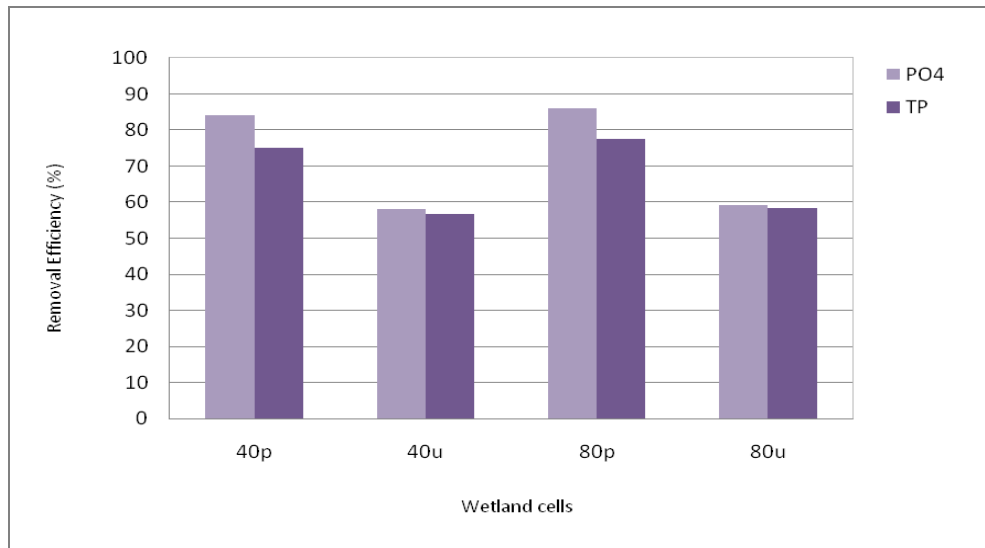


Figure 4-4: TP and $\text{PO}_4^{3-}\text{-P}$ removal efficiency

From figure 4.4, the removal efficiency of the H40p, H40u, H80p and H80u cells for TP was 75 %, 57 %, 77 % and 58 %, respectively, and for PO_4^{3-} it was 84 %, 58 %, 86 % and 59 %, respectively. As can be seen from the result, the planted wetlands led to a better removal of TP and $\text{PO}_4^{3-}\text{-P}$. Statistical analysis showed that there was a significant effect of plants ($p < 0.05$) in the percentage removal of these parameters, but depth effect was not significant. The reduction of phosphorus in wetlands is based mainly due to plant uptake and biotic assimilation, substrate adsorption and complexation/precipitation (UN-HABITAT, 2008).

The effluent concentration values of total phosphorous and orthophosphate from the wetlands were compared with the national effluent emission standard limit for winery wastewater. The discharge limit value set by EEPA was 5 mg/L for both parameters. The result showed that the obtained effluent concentration values of orthophosphate and total phosphorous met the limit values for all wetland cells, except by H40u for total phosphorous.

4.3 Model results

The performance evaluation on the four pilot scale constructed wetlands was used to design a large scale constructed wetland for wastewater treatment from Awash winery. The data analysis indicated that the 40cm deep planted unit had enhanced removal efficiency compared to the other units. Thus, it was considered in the design of a large scale constructed wetland.

This section presents the result and discussion of a model that had been simulated on the hydrologic dynamics of a large scale constructed wetland treating effluent from Awash winery. In this study, STELLA software was used to develop the model. Model development details are presented in chapter three.

4.3.1 Model simulation

The system water balance model diagram is shown in figure 4.5. The model consist one stock representing the constructed wetland water volume and four flows representing inflow, outflow precipitation and evapotraspiration. Stocks are represented by rectangles and represent variables that are capable of accumulating a substance over time. Flows are shown by circles with a small cloud attached to arrows leading into and out of a stock and represent actions that either increasing or decrease the value of a stock.

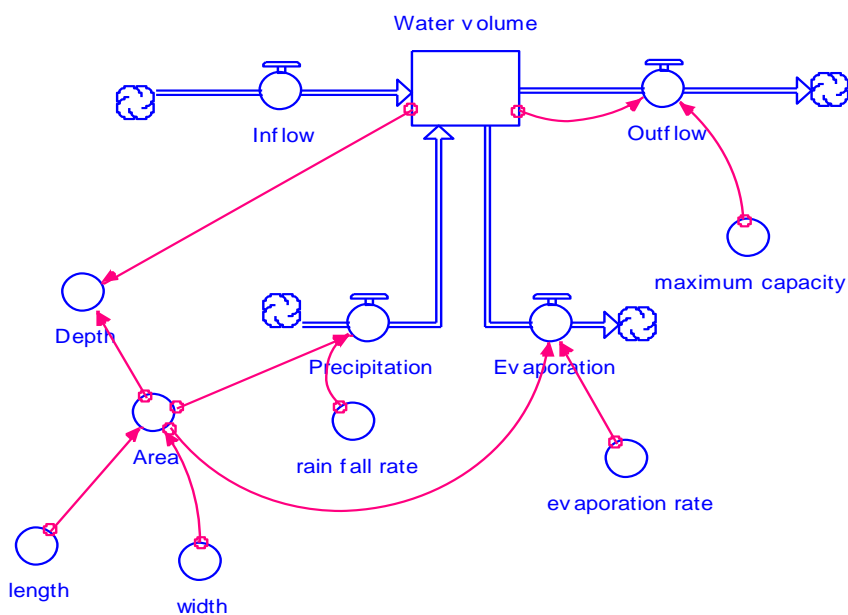


Figure 4-5: STELLA diagram of water balance in HSSFCW

Figure 4.6 illustrates the relationship between influent rate, water volume, water level and effluent rate in the wetland. The model was run with parameter values of 28 m³ daily inflow rate to accommodate the wastewater production rate of the winery, 42 m wetland length, 14 m wetland width and 0.9 m water depth. A constant influent rate is introduced to the wetlands and water volume increases to its maximum capacity. Once the maximum capacity is reached, the wetland begins to release water and has both an inflow and outflow. There is no outflow until the water volume in the wetland exceeds its capacity. The constructed wetlands outflow is assumed managed by a water control structure so that a constant volume can be maintained. The time for the start of the outflow denotes the detention time. The detention time of the constructed wetland was 10 days.

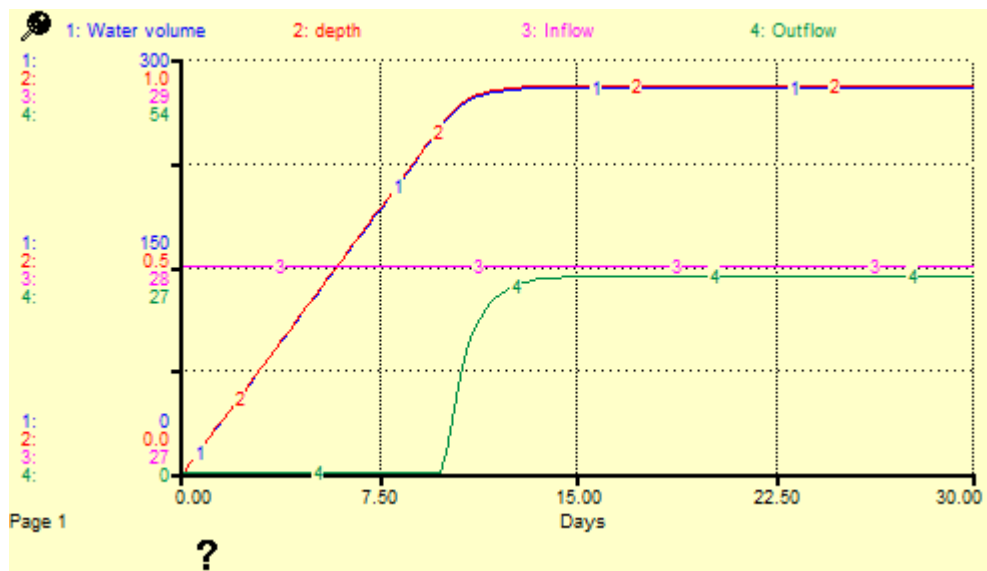


Figure 4-6: Water budget diagram of a large scale constructed wetland for Awash winey

4.3.2 Verification

Verification is the process used to assure that the model is correct and matches any agreed-upon specifications and assumptions. This can be done by running the model over a range of input parameters. Then, examine trends in the output measures when some input is changed; usually the direction if not the magnitude is known (Carson J.S., 2002). In this study, for verification, the model was run several times by varying the constructed wetland influent rate and surface area. Table 4.2 summarizes the generated retention time corresponding to the changing input parameters.

Table 4-2: Detention time

Area: 432 m²

Inflow rate (m³/day)	20	28	36	44
HRT (days)	10.25	7.25	5.5	4.5

Area: 588 m²

Inflow rate (m³/day)	20	28	36	44
HRT (days)	14.5	10	7.75	6.25

Area: 630 m²

Inflow rate (m³/day)	20	28	36	44
HRT (days)	15.75	10.75	8.25	6.75

Trends resulting from varying parameter values are a reduction in hydraulic retention time as inflow rate increased, due to hydraulic over loading. Also, as the surface area was changed it affected the retention time; it has a direct relationship. The outputs of the model for the above runs showed that they match agreed-upon expectations, which implies implementation of the model was done correctly. The design value proposed for effluent treatment from Awash winery is an area of 588 m² with daily inflow rate of 28 m³, to accommodate the wastewater production rate and meet the desired retention time of ten days with the minimum area possible.

CHAPTER 5 CONCLUSION AND RECCOMENDATION

5.1 Summary and Conclusions

The winery industry is one of the largest industrial users of water with effluent characterized by high levels of organic matter, nutrients and solids. The disposal of untreated wastewater from wineries poses a serious environmental problem, causing surface and groundwater pollution, soil degradation, damage to vegetation, and odor disturbances (Litaor M.I). With the increasing pressure from the environmental regulations and the growing awareness of the negative impacts of untreated wastewater, this industry is facing greater restrictions related to the discharge of their wastewater. Therefore, there is a need for a sustainable technology that can reliably achieve acceptable effluent quality for discharge into the environment at minimal cost.

Treatment wetlands have been used as a cost-effective and environmentally conscious treatment technology for improving final effluent quality of wastewater. There are a growing number of applications of wetlands dealing with domestic and municipal wastewater, animal and industrial waters, agricultural waters, mine waters and other applications (Kadlec and Wallace, 2009). However, data on winery wastewater treatment in constructed wetlands are very few while performance data that can guide design and operation under tropical environment conditions are lacking. This study was undertaken to explore the efficacy of constructed wetland technology planted with local emergent macrophytes in treating winery wastewater under tropical environment conditions. The use of constructed wetlands for winery wastewater treatment offer the advantages of low operating costs and the ability to assimilate the variably high organic loadings characteristic of winery wastewater production.

The constructed wetlands in this study acted as a secondary systems receiving treated wastewater from a sedimentation tank, which served as a primary treatment. The data from the HSSF constructed wetlands were used to evaluate the performance of the systems with respect to removal of organic matter (BOD, COD), suspended solids (TSS) and dissolved solids (TDS), and nutrients (N, P).

The study revealed that the mean removal efficiency of the wetlands for COD and BOD was in the range of 68% - 83% and 52% - 74%, respectively. The performance of the planted cells was better than the control (unplanted) cells. This could be due to plants contribution to oxygenation of the wetland beds. In this study the final effluent concentration of COD and BOD,

despite being weaker than the influent, wastewater does not comply with the national discharge limits. The constructed wetlands effectively removed TSS (up to 68.5 %) and TDS (up to 61%) from the wastewater to concentrations below that prescribed by the regulating authority in Ethiopia.

Mean nitrogen removal efficiency was in the range of 31% - 63%, 32% - 72% and 23% - 48% for TKN, NH_4^+ and NO_3^- respectively. For phosphorus, removal efficiencies ranged from 56% - 77% for TP and 58% - 86% for PO_4^{3-} . The efficiency of nutrient removal was higher in the planted cells than the control due to plant uptake associated with growth. The roots of macrophytes also release oxygen, producing a highly oxygenated environment that can be used by the nitrifying bacteria to proliferate. Except for NH_4^+ , the final effluent concentration of the other parameters from the four constructed wetlands met the discharge limit set by EEPA.

In this study, the effect of depth was significant in the removal of COD, BOD, TKN and NH_4^+ . The 40 cm deep cells showed higher percentage removal than the 80 cm deep cells. This is likely due to CWs with a lower depth having higher levels of dissolved oxygen. This can be due to the diffusion path between the surface and CW bed being shorter along with the oxygen release by macrophytes to the rizhosphere.

The 40cm deep planted cell had better overall performance compared to the other cells and thus was used in the design of a large scale constructed wetland for Awash winery. STELLA dynamic modeling tool was used to simulate the hydrologic dynamics of the wetland. The designed values for the wetland were inflow rate of 28 m³/day, 42 m wetland length, 14 m wetland width and 0.9 m weted depth. This can accomodate the wastewater production rate of the winery and meet the desired retention time of ten days with minimum area possible.

In general, the findings of this study showed encouraging performance of constructed wetland system with respect to the removal of the pollutants monitored. In developing countries like Ethiopia, conventional technologies for wastewater treatment may not be economically feasible. Hence, constructed wetlands may offer low-cost, low maintenance and energy efficient alternative, provided that wineries have enough available land for wetland creation.

5.2 Recommendation

This study showed positive results on the potential of constructed wetlands in treating winery wastewater. Based on the findings of the study, for effective performance of this technology the following points are recommended.

The effluent concentration values of some parameters for some of the wetlands were above the discharge limits set by National Environmental Quality Standard. Thus, in order to enhance the removal efficiency, different types of constructed wetlands may be used in combination. HSSFCWs may be used with vertical flow wetlands and/or FWS wetlands as a hybrid system to improve the level of oxygen transfer and also achieve overall higher performance.

When the performances of the 40 cm and 80 cm deep wetland cells at the same hydraulic residence time were compared, the 40 cm deep cells had lower or significantly not different effluent concentration than the 80 cm deep cells. Hence, based on this study, water depth equal to the root depth is recommended, as this will reduce cost of construction. There could be little or no benefit in having CWs with depths that are beyond this.

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